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14. ABSTRACT
This project dealt with computational methods for optical imaging. Applications of particular interest the the Air Force included
1. Wavefront reconstruction (i.e., estimation and control of wavefront aberrations) in ground-based adaptive optics systems.
2. Modelling and control of micro electromechanical systems (MEMS) deformable mirrors for adaptive optics.
3. Estimation of the motion of an object from a sequence of frames of scanned image data.

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FINAL REPORT

June 1, 2002 to May 31, 2006

Computational Methods in Advanced Imaging Sciences

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Contents

1 Introduction

This project dealt with computational methods for optical imaging. Applications of particular interest the the Air Force included

1. Wavefront reconstruction (i.e., estimation and control of wavefront aberrations) in ground-based adaptive optics systems.

2. Modelling and control of micro electromechanical systems (MEMS) deformable mirrors for adaptive optics.

3. Estimation of the motion of an object from a sequence of frames of scanned image data.

Of fundamental importance in the first application is the aperture-plane phase, or wavefront aberration, $\phi(x, y)$. This can be interpreted as the deviation from planarity of the wavefront of light, at planar incidence at the top of the earth's atmosphere, after it has propagated through the atmosphere [7]. Assuming an incoherent light source, the on-axis point spread function takes the form

$$s = |\mathcal{F}(Ae^{i\phi})|^2, \tag{1}$$

where $\mathcal{F}$ denotes the two-dimensional Fourier transform, $i = \sqrt{-1}$, and A denotes the aperture function. For an ideal telescope, $A = 1$ inside the telescope aperture, and $A = 0$ outside the aperture.

Since the point spread function determines optical image quality, accurate control of the wavefront enables one to obtain high-quality images. The basic concept underlying the field of *adaptive optics* (AO) is the control of the wavefront through the use of deformable mirrors [6]. In addition to deformable mirrors, a typical AO system consists of sensors to measure the wavefront and a control system which maps sensor measurement to mirror actuator commands. The Air Force has long had an interest in AO and maintains two large facilities for AO-assisted ground-based imaging of space objects—one on the island of Maui in Hawaii and the other at the Starfire Optical Range in New Mexico.

Since atmospheric wavefront aberrations evolve on millisecond time scales and an AO system my have hundreds or even thousands of actuators and sensors, real-time wavefront control can be quite challenging. The PI helped develop a new class of fast computational algorithms for wavefront estimation

and control. These algorithms are based on the preconditioned conjugate gradient method [5] and make use of preconditioners that were tailored to fit the special structure of the linear algebraic systems that arose. These included multigrid preconditioners for conventional, or single-conjugate, AO [3, 4, 9] and Fourier-domain preconditioners for a variant called multi-conjugate AO, which relies on multiple deformable mirrors and sensors in multiple directions to sense the atmosphere in a tomographic manner [12, 13].

MEMS deformable mirrors are a relatively new technology for AO. These devices are very fast, relatively inexpensive, and may allow extremely high resolution wavefront control. In [11] the PI introduce a new model for MEMS deformable mirrors. It relies on a 4th order linear PDE known as the plate equation to model the facesheet of the mirror. The mirror actuators are modelled using nonlinear algebraic equations which are coupled to the linear PDE. Efficient computational techniques to solve the model equations and to control the MEMS mirror were also developed by the PI and are presented in [11].

Vision science—the study of the mammalian vision system—is another very important application area for AO. Using deformable mirrors, one can compensate for wavefront aberrations caused by imperfections in the lens of the eye and obtain nearly diffraction-limited images of the living retina [2]. The usefulness of these images has been limited by motion of the retina that occurs on time scales that are comparable to the time needed to acquire the images using scanning devices. The estimation of motion from a sequence of frames of scanning data is an interesting inverse problem which has applications in a number of other important areas. In [10], the PI and his collaborators presented a robust, efficient solution to this problem that made use of a novel technique known as the map-seeking circuit algorithm [1].

2 Objectives

The broad objective of this project was the development of efficient computational algorithms to solve important problems in optical imaging. This provided support for the Air Force's Partnerships for Research Excellence and Transition (PRET) in Advanced Imaging Sciences, whose goal was to enhance space situational awareness capabilities. The project focused on an advanced optical image enhancement technology known as adaptive optics. Specific goals were to develop fast algorithms for wavefront reconstruction

(i.e., estimation and control of wavefront aberrations in an optical system) and the modelling, simulation, and control of hardware devices used in adaptive optics.

3 Major Accomplishments and New Findings

Major accomplishments of this project included

- The development of fast, robust new algorithms for wavefront reconstruction. These are described in peer-reviewed publications [3, 4, 9, 12, 13]. These new algorithms are now being integrated into the design of a thirty-meter ground-based optical telescope (TMT). For details, visit the TMT web site [8].

- The development of a new model for micro electro-mechanical systems (MEMS) deformable mirrors for adaptive optics. The peer-reviewed publication [11] describes the model, and numerical simulations and control for this device. A provisional patent was issued for the model and the control scheme.

- The development of a fast, robust new scheme to estimate object motion from a sequence of scanned images. This is described in the peer-reviewed publication [10]. A provisional patent was issued for the scheme, and an international IPT patent is being processed. This motion estimation scheme is now being implemented in hardware for real-time tracking of the retina of the human eye.

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[1] D.W. Arathorn, *Map-Seeking Circuits in Visual Cognition*, Stanford University Press, 2002.

[2] J. Carroll, D.C. Gray, A. Roorda, and D.R. Williams, *Recent advances in retinal imaging with adaptive optics*, Optics and Photonics News, January 2005, pp. 36-42.

[3] Luc Gilles, C.R. Vogel, and Brent Ellerbroek, *A Multigrid Preconditioned Conjugate Gradient Method for Large Scale Wavefront Recon-*

struction, Journal of the Optical Society of America A, **19** (2002), pp. 1817-1822.

[4] Luc Gilles, B.L. Ellerbroek, and C.R. Vogel, *Preconditioned Conjugate Gradient Wavefront Reconstructors for Multi-Conjugate Adaptive Optics*, Applied Optics 42 (2003), pp. 5233–5250.

[5] G.H. Golub and C.F. VanLoan, *Matrix Computations, 2nd Edition*, Johns Hopkins University Press, 1989.

[6] J. W. Hardy, *Adaptive Optics for Astronomical Telescopes*, Oxford Press, 1998.

[7] M. C. Roggemann and B. Welsh, *Imaging Through Turbulence*, CRC Press, Boca Raton, 1996.

[8] Thirty Meter Telescope (TMT) Project web site, `http://www.tmt.org/`

[9] C.R. Vogel and Q. Yang, *Multigrid algorithm for least squares wavefront reconstruction*, Applied Optics, 45 (2006), pp. 705-715.

[10] C.R. Vogel, D.W. Arathorn, A. Roorda, and A. Parker, *Retinal motion estimation and image dewarping in adaptive optics scanning laser ophthalmoscopy*, Optics Express, 14 (2006), pp. 487-497.

[11] C.R. Vogel and Q. Yang, *Modelling, simulation, and open-loop control of a continuous facesheet MEMS deformable mirror*, Journal of the Optical Society of America-A, 23 (2006), pp. 1074-1081.

[12] Q. Yang, C.R. Vogel and B. Ellerbroek, *Fourier domain preconditioned conjugate gradient algorithm for atmospheric tomography*, Applied Optics 45 (2006), pp. 5281-5293.

[13] C.R. Vogel and Q. Yang, *Fast optimal wavefront reconstruction for multi-conjugate adaptive optics using the Fourier domain preconditioned conjugate gradient algorithm*, Optics Express, to appear.

4 Personnel Supported by Grant

- The PI: Curtis R. Vogel, Professor of Mathematics, Montana State University.

- 3 Postdoctoral Research Associates: Dr. Luc Gilles, Dr. Mike Flanagan, and Dr. Qiang Yang. Dr. Gilles is now employed as an adaptive optics systems analyst with the Thirty Meter Telescope project in Pasadena, California. Dr. Flanagan is employed with the TREX corporation, an Air Force subcontractor in Maui, Hawaii. Dr. Yang is employed as a Research Associate for the Center for Computational Biology at Montana State University.
- 1 Graduate Research Assistant: Jennifer Thorenson. Ms. Thorenson completed her Master's degree in Mathematics and has entered the PhD program at Montana State University.

5 Publications

1. B.L. Ellerbroek, Luc Gilles, and C.R. Vogel, *Numerical simulations of multiconjugate adaptive optics wavefront reconstruction on giant telescopes*, Applied Optics 42 (2003), pp. 4811–4818.
2. Luc Gilles, B.L. Ellerbroek, and C.R. Vogel, *Preconditioned Conjugate Gradient Wavefront Reconstructors for Multi-Conjugate Adaptive Optics*, Applied Optics 42 (2003), pp. 5233–5250.
3. B.L. Ellerbroek and C.R. Vogel, *Simulations of closed-loop wavefront reconstruction for multiconjugate adaptive optics on giant telescopes*, Proc. SPIE 5169-23, Adaptive Optics System Technologies II (2003), pp. 206–217.
4. C.R. Vogel, *Sparse matrix methods for wavefront reconstruction revisited*, Proc. SPIE 5490-60, Advancements in Adaptive Optics (2004), pp. 1327-1335.
5. J.M. Bardsley and C.R. Vogel, *A nonnegatively constrained convex programming method for image reconstruction*, SIAM Journal on Scientific Computing, 25 (2004), pp. 1326-1343.
6. C.R. Vogel and Q. Yang, *Multigrid algorithm for least squares wavefront reconstruction*, Applied Optics, 45 (2006), pp. 705-715.

7. C.R. Vogel, D.W. Arathorn, A. Roorda, and A. Parker, *Retinal motion estimation and image dewarping in adaptive optics scanning laser ophthalmoscopy*, Optics Express, 14 (2006), pp. 487-497.

8. C.R. Vogel and Q. Yang, *Modelling, simulation, and open-loop control of a continuous facesheet MEMS deformable mirror*, Journal of the Optical Society of America-A, 23 (2006), pp. 1074-1081.

9. Q. Yang, C.R. Vogel and B. Ellerbroek, *Fourier domain preconditioned conjugate gradient algorithm for atmospheric tomography*, Applied Optics 45 (2006), pp. 5281-5293.

10. Q. Yang and C.R. Vogel, *Fourier domain algorithm for the fitting step in multi-conjugate adaptive optics*, Proc. SPIE 6272-101, Advances in Adaptive Optics II (2006).

11. C.R. Vogel and Q. Yang, *Modelling and open-loop control of point-actuated, continuous facesheet deformable mirrors*, Proc. SPIE 6272-73, Advances in Adaptive Optics II (2006).

12. C.R. Vogel, *Time-Varying Stochastic Turbulence Model*, Proc. SPIE 6272-112, Advances in Adaptive Optics II (2006).

13. C.R. Vogel and Q. Yang, *Fast optimal wavefront reconstruction for multi-conjugate adaptive optics using the Fourier domain preconditioned conjugate gradient algorithm*, Optics Express, to appear.

6 Collaborative Research and Transactions at US Air Force Laboratories

The PI's work under this grant was carried out in collaboration with the Partnerships for Research Excellence and Transition (PRET) in Advanced Imaging Sciences. During the course of this project, the PI visited Air Force research facilities on the island of Maui, Hawaii. He met with fellow researchers at the Maui High Performance Computing Center (MHPCC) on the following occasions:

1. August 21-23, 2002. The PI presented a series of 3 tutorial lectures on multi-conjugate adaptive optics at the Maui Scientific Research Center (MSRC).

2. January 14-16, 2003. The PI attended the annual PRET meeting at the MHPCC and presented a talk "An order N algorithm for least squares wavefront reconstruction".

3. June 2-5, 2003. The PI presented 3 lectures in a short coarse on inverse problems in optics at the MSRC.

4. January 19-21, 2004. The PI attended the annual PRET meeting at the MHPCC and presented a talk "Estimating object motion from scanned image data".

7 Inventions or Patent Disclosures

1. U.S. Provisional Patent "Application of map-seeking circuit algorithm to determine movement between time separated image frames and de-warping of movement-induced warpage", filed by David W. Arathorn and Curtis R. Vogel on June 10, 2004.

2. International PCT Patent Application "System and Method for Determining Arbitrary, Relative Motion Estimates between Time-Separated Image Frames"; filed by Montana State University in behalf of David Arathorn and Curtis R. Vogel, June 16, 2005.

3. U.S. Provisional Patent "Algorithm for Simulation and Open-Loop Control of Non-Hysteretic Continuous Facesheet Deformable Mirrors", filed by Curtis R. Vogel and Qiang Yang on July 29, 2005.

Within one year of filing, provisional patents must either be upgraded or they will lapse. The second patent is an upgraded version of the first. PCT stands for "Patent Cooperation Treaty"; this means that we have filed for international patent protection of our invention. The third patent was allowed to lapse.

8 Summary

This project dealt with the development of fast, robust new computational methods for imaging sciences. It focused on adaptive optics wavefront reconstruction, MEMS deformable mirror modelling and control in adaptive

optics, and retinal motion estimation in vision science. A total of 13 peer-reviewed scientific journal articles were prepared under this grant and one graduate student and 3 postdoctoral researchers were supported. In addition, 2 provisional patents were issued for inventions which were developed under this project. One of the provisionals has been converted to an international patent in accordance with the International Patent Cooperation Treaty; the second has been allowed to lapse.

Two of the algorithms developed under this grant are being implemented in scientific projects. One of our wavefront reconstruction algorithms is now being applied to the control system for the Thirty Meter Telescope, and our motion estimation algorithm is being implemented in hardware to track the motion of the retina of the eye.